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| 14. ABSTRACT The major goal of the project was to characterize variability of the Kuroshio east of Taiwan and to understand (1) how this variability is related to variability in the upstream region, where the North Equatorial Current bifurcates forming the northward-flowing Kuroshio and the southward-flowing Mindanao Current and (2) how westward-propagating mesoscale eddies that arrive along Taiwan from the North Pacific ocean interior shape Kuroshio variability. The project's analysis and data integrations will help establish the advective versus the eddy-driven contributions to Kuroshio variability east of Taiwan. | | | | | |
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Eddies and the Kuroshio between Luzon and Northeastern Taiwan: Integration of In Situ Observations and Remote Sensing Data

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1. Long Term Goals

The major goal of the project was to characterize variability of the Kuroshio east of Taiwan and to understand (1) how this variability is related to variability in the upstream region, where the North Equatorial Current bifurcates forming the northward-flowing Kuroshio and the southward-flowing Mindanao Current and (2) how westward-propagating mesoscale eddies that arrive along Taiwan from the North Pacific ocean interior shape Kuroshio variability. The project's analysis and data integrations have helped establish the advective versus the eddy-driven contributions to Kuroshio variability east of Taiwan.

A further goal of the project was to develop the methodology to integrate measurements from different platforms—upward-looking acoustic Doppler current profilers (ADCPs), bottom-moored pressure-sensor-equipped inverted echo sounders (PIESs) and gliders—in order to leverage the strength of each instrument type and to minimize errors.

2. Objectives

The objective of this project was to analyze data from the western North Pacific (**Figure 1**) that were collected through a previous field program east of Taiwan in a joint U.S.-Taiwanese collaboration. The field program comprised moorings and shipboard observations across the Kuroshio east of Taiwan, just upstream of the East China Sea. In addition to processing and analyzing the *in situ* data from the moorings, the project integrated the observations with other data sets that have been collected through the Observations of Kuroshio Transports and Variability (OKTV) Program, which was sponsored by the Taiwanese National Science Council/Ministry of Science and Technology (NSC/MOST), and the ONR-sponsored Origins of the Kuroshio and Mindanao Currents (OKMC) DRI. A figure showing both instrument arrays is attached (**Figure 2**).

3. Approach

Through this project, methods have been developed to integrate temperature and salinity profiles collected from Seaglider sections with time series measurements from PIESs deployed in fixed stands on the seabed northeast of Luzon and east of Taiwan. Further, methods have been developed to use data from upward-looking ADCPs to 'level' PIES instruments (**Figure 3**). In addition, sea surface height (SSH) maps from satellite altimetry were used to provide context for the observations collected by the *in situ* arrays.

4. Tasks Completed

Using the approach outlined above, time series of transport and velocity structure for the Kuroshio northeast of Luzon and east of Taiwan have been calculated and the role of mesoscale eddies in modulating the Kuroshio has been investigated. The procedures were first implemented and evaluated for the instrument array deployed east of Luzon and were published in the *Journal of Atmospheric and Oceanic Technology* (Mensah et al., 2016). The procedures were then implemented for the instrument array deployed east of Taiwan and the science results from this will be submitted shortly to the *Journal of Geophysical Research* (Andres et al., 2016). Comparisons of the *in situ* data with satellite altimetry data were published in *Geophysical Research Letters* (Tsai et al., 2015). In addition to these peer-reviewed publications, results have been presented at PI meetings, at U.S. and international science meetings (Jan et al 2016; Andres et al., 2015), and in review papers in a special issue of *Oceanography* (Andres et al., 2015; Yang et al., 2015 and Lien et al., 2015).

This project provided the basis for the Master's Thesis research of C.-J Tsai, a student at National Taiwan University (Tsai 2015). Her work examined the effect of mesoscale eddies on the thermocline east of Taiwan and east of Luzon, Philippines. The major finding of this research was that eddies arrivals near the western boundary—as observed in mapped sea surface height measured by satellite altimetry—coincide with thermocline displacements—as detected by the PIESS' acoustic travel time measurements (**Figure 4**).

The project also provided a basis for part of a research effort by a postdoc at National Taiwan University (Dr. V. Mensah). This research developed and optimized the methodology to combine PIESS measurements with collocated observations from gliders and ADCPs (Mensah et al., 2016 and **Figure 5**). This combination has allowed us to explore the dynamics of the Kuroshio and of eddy-Kuroshio interactions.

Both Tsai and Mensah are in the research group at National Taiwan University of Dr. S. Jan.

Through this project, two Woods Hole Oceanographic Institution (WHOI) technicians (B. Hogue and A. Davies) were trained in PIESS instrument refurbishments, together with three visiting collaborators from National Taiwan University (S.-C. Shie, B. Wang, N. Taniguchi). The training was part of a workshop held at WHOI in January 2016, led by an engineer from the University of Rhode Island (where the PIESS are manufactured and developed). The five PIESS instruments, comprising both WHOI and National Taiwan University PIESS, had been used in the field east of Taiwan through the OKMC/OKTV projects and have recently been redeployed east of Taiwan as part of the SK-II array.

5. Results

Synthesis of the observations from the two companion field programs east of Taiwan and northeast of Luzon allowed examination of the temporal and spatial evolution of the Kuroshio between its origin and its passage into the East China Sea. Kuroshio strength and velocity

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structure were measured between June 2012 and November 2014 using arrays comprising pressure-sensor equipped inverted echo sounders (PIESs) and upward-looking acoustic Doppler current profilers (ADCPs) deployed across the current northeast of Luzon, Philippines and east of Taiwan with an eight-month overlap in the two arrays' deployment periods. The Kuroshio's mean net absolute transport in the upper 1000 dbar increases downstream from 14.3 Sv (mean standard error, $mse = \pm 2.8$ Sv) northeast of Luzon to 21.3 Sv ($mse = \pm 2.6$ Sv) east of Taiwan, and is accompanied by an increase in the depth of the Kuroshio's poleward flow in the mean velocity sections. Northeast of Luzon, the 0 m s^{-1} isotach is shallower than 750 dbar, while east of Taiwan there are areas of positive flow that reach to the seafloor (3000 m). At both arrays, there is a deep counterflow beneath the poleward-flowing Kuroshio (-10.3 ± 2.3 Sv by Luzon and -12.5 ± 1.2 Sv east of Taiwan). Time-varying transports and velocities at each section indicate the strong influence at both sections of westward propagating eddies that arrive from the ocean interior. These eddies have an expression both in the thermocline and in the deep ocean (**Figure 6**). Topography associated with the ridges east of Taiwan also exerts an influence on the mean and time-varying velocity structure there.

6. Impact for Science

The work completed through this project highlights the importance of topography in shaping the mean flow. Additionally, the work suggests that eddies in the western North Pacific have a deep expression. The interaction of deep-reaching eddies with topography is important for controlling the time-varying flows in the western North Pacific. This work also adds to our understanding of eddy-mean flow interactions.

7. Relationship to Other Programs

This project synthesizes observations from two companion field programs—Origins of the Kuroshio and Mindanao Currents (OKMC) funded by the Office of Naval Research and Observations of Kuroshio Transport Variability (OKTV) funded through the Ministry of Science and Technology (MOST). The major findings from this project have motivated an additional field program (2016-2017) east of Taiwan (**Figure 7**), Study of the Kuroshio II, SK-II, funded by MOST.

8. Figures

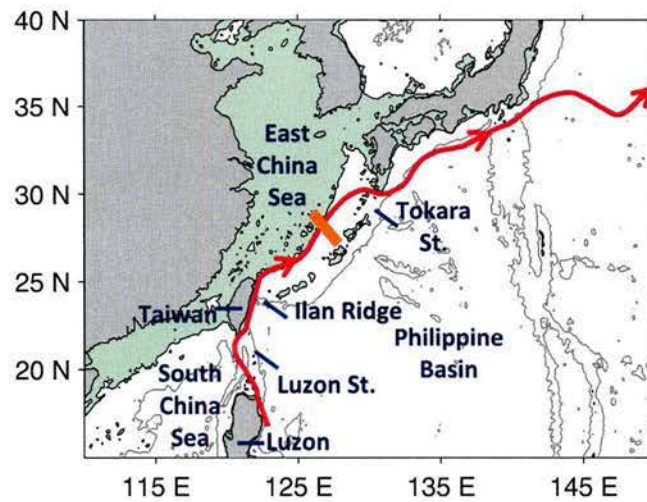


Figure 1. Map of the western North Pacific with the Kuroshio mean-path (red) and the 3000 m isobath (grey) shown. Regions shallower than 500 m depth are shaded (green).

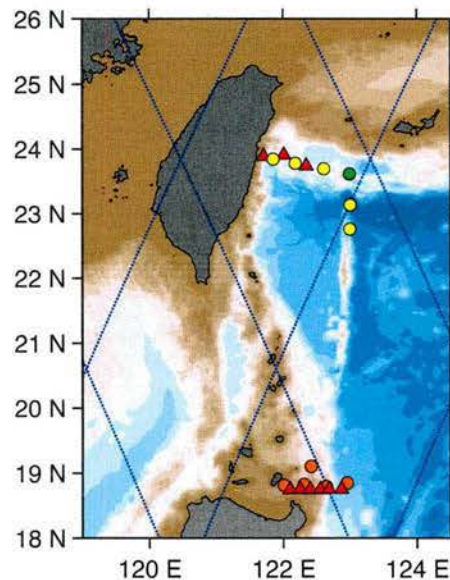


Figure 2. The OKMC/OKTV array east of Taiwan with ADCPs (red triangles), PIESs (yellow circles) and a CPIES (PIES with an additional current sensor, green circle) and the companion OKMC project east of Luzon with ADCPs (red triangles) and HPIES (PIES with an HEF sensor, orange circles). The experiments' deployment periods over-lapped for 6 months. Blue lines indicate Jason-2 satellite repeat tracks.

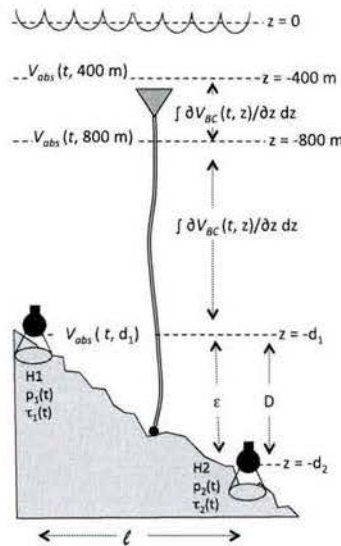


Figure 3. Schematic of the leveling procedure to use an upward-looking ADCP to level the neighboring PIESs (H1 and H2), from Figure 5 of Mensah et al., 2016.

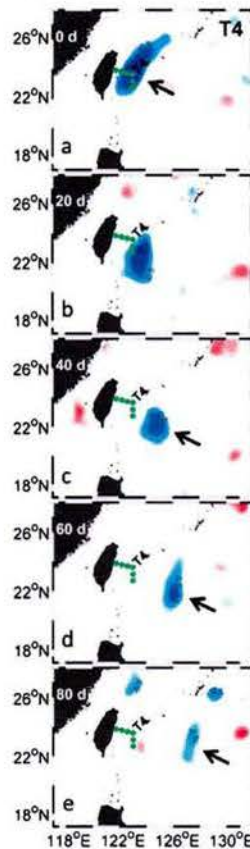


Figure 4. Lagged correlation maps showing that PIES-measured acoustic travel time site T4 (northeastern-most green dot east of Taiwan) is negatively correlated with the SSH associated with mesoscale eddies approaching the western boundary from the interior (Tsia et al., 2015).

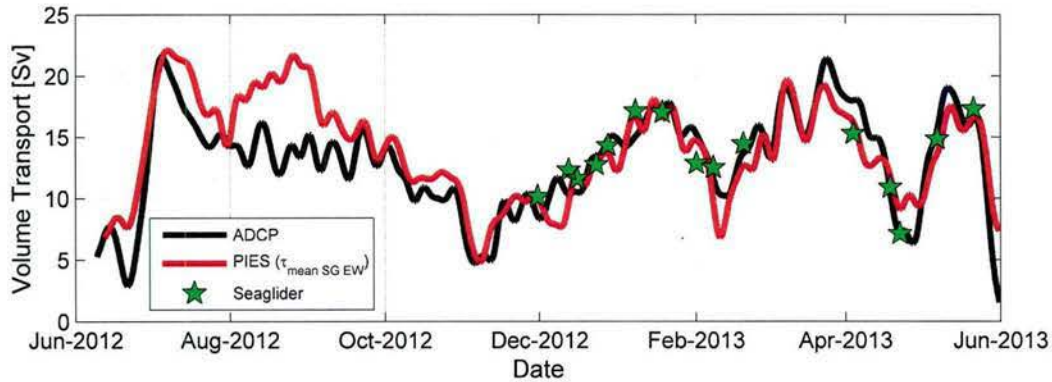


Figure 5. Integrated 0-600 dbar volume transport time series integrated between 122.10°E and 122.87°E east of Luzon (**Figure 2**) derived from the 6 ADCP moorings (black), from the PIES processed with newly developed processing scheme and from the Seagliders (green stars). Times of mismatch between the red and black curves likely denote periods of significant ageostrophic contributions to the net transport and are being investigated further. Adapted from Mensah et al., 2016.

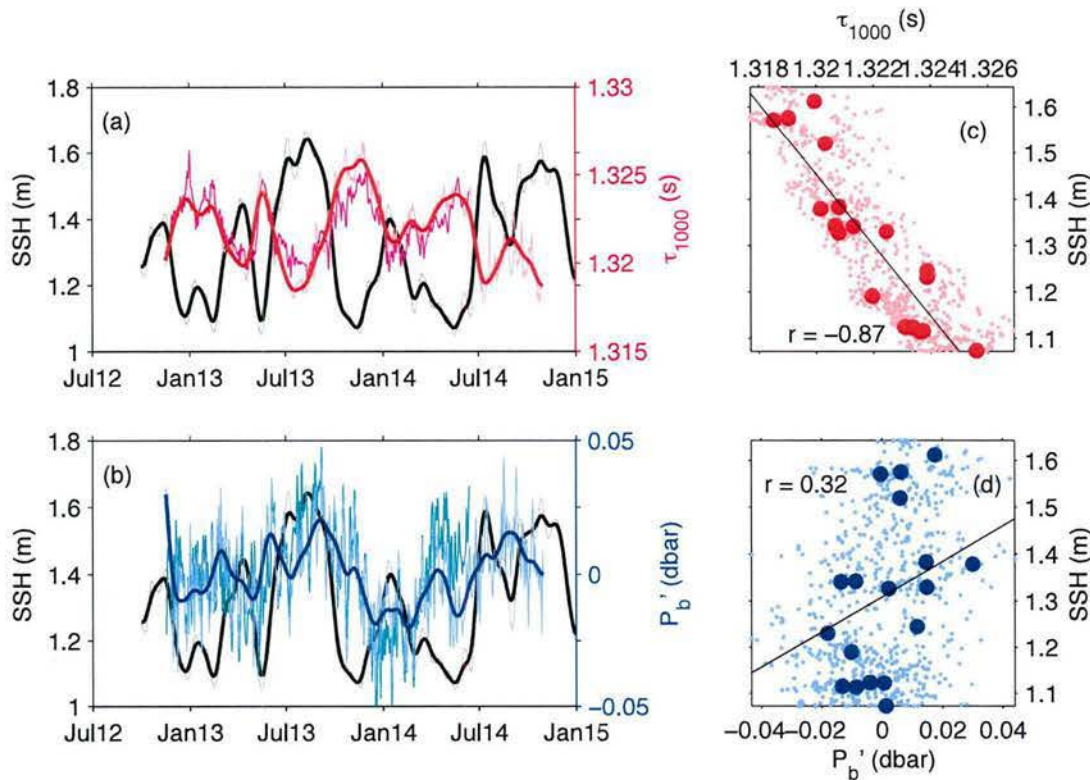


Figure 6. Panel (a): comparison of SSH and acoustic travel time records showing time series of the SSH (at 123°E, 23.375°N from the Aviso mapped absolute dynamic topography) daily product (gray) and with a 40-day low-pass filter applied (black). Also plotted is the time series of

the 3-day low-pass filtered t_{1000} from T-P5 (light red) with a 40-day filter applied (red); the shorter t_{1000} record from T-P4 is shown for comparison (magenta). Panel (b): comparison of SSH (as in a) with bottom pressure records showing the 3-day low-pass filtered P_b from T-P5 (light blue) and with a 40-day low-pass filter applied (heavy blue). The P_b record from T-P4 is shown for comparison (cyan). Panel (c) shows the negative correlation at T-P5 of SSH with t_{1000} for the total signals (light red dots) and the 40-day low-pass filtered records (heavy red dots, plotted for every 40th day). Panel (d) shows the positive correlation at T-P5 of SSH with P_b for the total signals (light blue dots) and the 40-day lowpass filtered records (heavy blue dots, plotted for every 40th day). Figure from Andres et al., (2016).

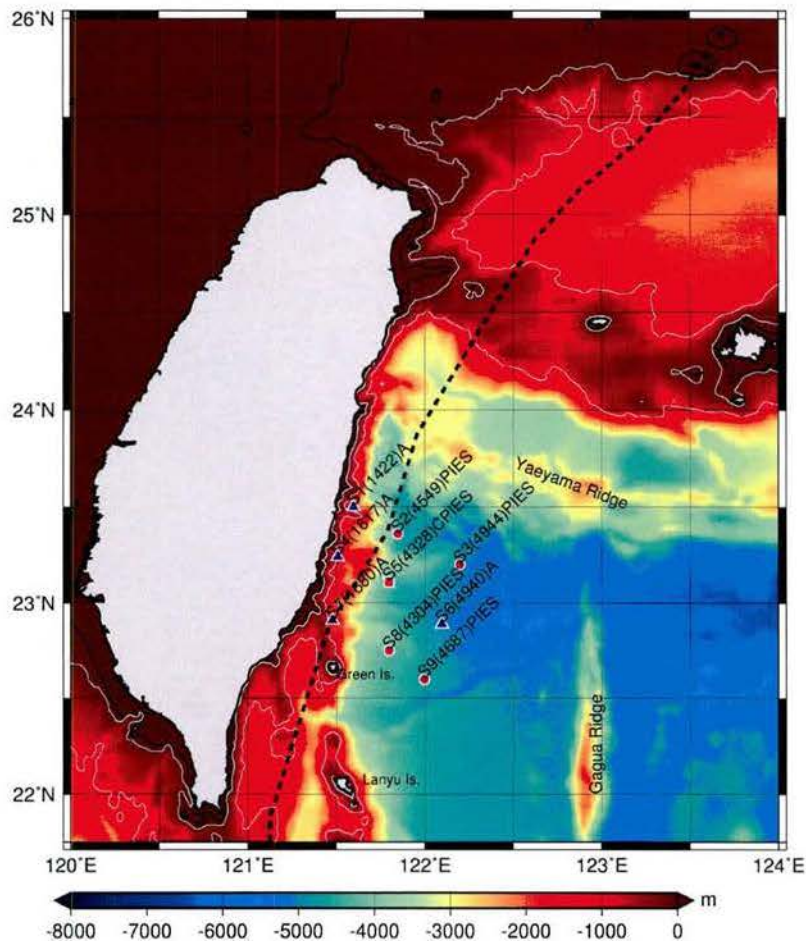


Figure 7. Recently deployed SK-II array, motivated in part by the findings from this study. These moorings will remain in the water from ~12 months and were deployed April 2016.

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